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Full-Scale Demonstration of Low-NO_x Cell Burner Retrofit: A DOE Assessment

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Executive Summary

This document serves as a U.S. Department of Energy (DOE) post-project assessment of a project in Clean Coal Technology (CCT) Round 3, Full-Scale Demonstration of Low-NO_x Cell™ Boiler (LNCB) Retrofit. In October 1990, the Babcock and Wilcox Company (B&W) entered into an agreement to conduct this study, with Dayton Power and Light (DP&L) as the host and cosponsor. The full-scale demonstration was conducted between December 1991 and May 1993.

This project was undertaken to evaluate the technical and economic feasibility of retrofitting LNCB technology for cell burner boiler NO_x emission control in electric power generation service. Most cell burner boilers use two-nozzle cell burners which fire pulverized coal under very high temperature combustion conditions.

Because of the high temperature of combustion in cell boilers, high levels of NO_x are formed. The LNCB retrofit technology replaces each two-cell burner (and some three-cell burner units) with one larger diameter burner nozzle to provide the same coal-firing capacity as the original two (or three) nozzles. This enlarged burner is fired under highly fuel-rich conditions, and the second-stage combustion air is introduced through the second nozzle of the original cell. The net result is a decrease in combustion temperatures under deeply staged conditions and a reduction in both fuel NO_x and thermal NO_x.

The performance objectives of this project were as follows:

1. To evaluate the ability of LNCB technology to reduce NO_x emissions at least 50% in full-scale boilers equipped with cell burners.
2. To achieve the NO_x reduction goal with no degradation of boiler performance or life of the unit.
3. To demonstrate that LNCB is an economically viable retrofit technology.

All three goals were met or exceeded in the demonstration project, which was conducted at DP&L's J.M. Stuart Station, Unit 4 (rated at 605 MWe). This boiler is fired with Midwestern bituminous coal with an average sulfur content of about 1%. Greater than 50% reduction of NO_x emissions was achieved at full and intermediate boiler loads, and nearly 50% at low boiler load. Waterwall corrosion was within normal limits for standard cell boilers.

Application of B&W's mathematical models led to the design of a modified LNCB firing configuration which mitigated excessive concentrations of CO and H₂S in the boiler hopper. No problems were experienced in boiler operation or other emissions under optimized conditions. DP&L accepted the LNCB firing system and continued to run it on a routine basis. B&W has retrofitted LNCB technology to nearly 5,500 MWe of generating capacity in the United States.

A 1994 estimate using a nominal 600-MWe unit gave an estimated capital cost for an LNCB retrofit of \$9/kW. Assuming uncontrolled NO_x emissions of 1.20 lb/10⁶ Btu, 50% NO_x reduction,

and a 15-year project life, the levelized cost on a current dollar basis is 0.37 mills/kWh. This is equivalent to \$125/ton of NO_x removed. On a constant dollar basis, the levelized cost is 0.28 mills/kWh, equivalent to \$97/ton.

Though plug-in burner technologies are the current commercial choice in the United States, Low-NO_x cell burners represent an effective, reliable, and easy-to-install retrofit combustion control technology for reducing NO_x emissions from cell burner boilers. Since a number of cell burner boilers have been sold outside the United States under B&W license, an international market may exist for this technology.

The LNCB project received *R&D Magazine's* 1994 R&D 100 award for technical excellence in a new commercial product.

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I Introduction

The goal of the U.S. Department of Energy (DOE) Clean Coal Technology (CCT) program is to furnish the energy marketplace with a number of advanced, more efficient, and environmentally responsive coal utilization technologies through demonstration projects. These projects seek to establish the commercial feasibility of the most promising advanced coal technologies that have developed beyond the proof-of-concept stage.

This document serves as a DOE post-project assessment of a project in CCT Round 3, "Full-Scale Demonstration of Low-NO_x CellTM Burner Retrofit." In October 1990, the Babcock and Wilcox (B&W) Company entered into a cooperative agreement to conduct the study. Dayton Power and Light (DP&L) was the host and cosponsor, with additional cofunding by the Electric Power Research Institute (EPRI), the Ohio Coal Development Office, and a number of electric utility companies. The demonstration was started up in December 1991 and was completed in May 1993. The independent evaluation contained herein is based primarily on information from the Final Project Report prepared by B&W, dated July 1994 [9], as well as other references cited.

Most cell burner boilers use two-nozzle cell burners (a few use three-nozzle cell burners) which fire pulverized coal under high-intensity combustion conditions. The resulting high temperatures lead to formation of significant amounts of NO_x. Standard low-NO_x burners (LNBs), which cannot be used in these boilers without pressure part modifications, would be relatively costly in this application.

B&W developed the Low-NO_x CellTM Burner (LNCB) technology. In this technology, a standard cell burner is replaced with an LNCB, which consists of a single lower coal nozzle and an upper secondary air port. The secondary air port, sometimes referred to as the overfire air (OFA) port, is designated by B&W as the NO_x port. Approximately 60-70% of the air theoretically required for complete combustion is provided to the lower nozzle, along with the coal. The remainder of the air is introduced through the NO_x port.

The deep air staging resulting from the LNCB retrofit delays the mixing of coal and combustion air, so that combustion occurs under lower temperature and fuel-rich, reducing conditions. The net result is a reduction in both thermal NO_x and fuel NO_x emissions.

B&W investigated the LNCB concept in a laboratory test program in the early 1980's. The results showed that LNCB maintains a stable flame throughout the operating range and that the expected reduction in NO_x emissions is about 50%. B&W concluded that LNCB retrofit technology could be applied to all of the two-nozzle cell burner boilers in the United States. The purpose of this project was to demonstrate LNCB technology on a commercial scale.

The host site chosen for this CCT demonstration project was DP&L's J.M. Stuart Station, Unit 4 (JMSS4), located in Aberdeen, Ohio. The unit is a once-through, positive pressure cell burner boiler, with two rows of six two-nozzle cell burners in both its front and rear walls, for a total of

48 coal-fired burners in 24 cells. At 605 MWe rated capacity, this unit is a typical size for cell burner boilers. There are 38 cell burner boilers in the United States, having a total capacity of about 26,700 MWe. This comprises about 13% of the U.S. coal-fired generating capacity.

The performance objectives of this project were as follows:

1. To demonstrate the ability of LNCB retrofit technology to reduce NO_x emissions at least 50% in full-scale boilers equipped with cell burners.
2. To achieve the NO_x reduction goal with no degradation of boiler performance or life of the unit.
3. To demonstrate that LNCB is an economically viable retrofit technology.

II Technical and Environmental Assessment

A. Promise of the Technology

This project was undertaken to evaluate the technical and economic feasibility of using LNCBs as a retrofit technology for reducing NO_x emissions in coal-fired cell burner boilers. This demonstration, which involved a commercial-scale implementation of the technology, was supported by the results of previous B&W studies:

1. The LNCB technology was investigated in B&W laboratory and pilot-scale test programs supported by EPRI in the early 1980's. The test programs indicated that LNCBs could maintain a stable flame throughout the operating range, and that at least 50% NO_x reduction was achievable with acceptable impacts on carbon monoxide (CO), unburned carbon (UBC), and furnace exit gas temperature (FEGT).
2. One of the standard two-nozzle cell burners in Unit 3 at JMSS4 was replaced by an LNCB in 1985. The objective of this replacement was to evaluate the long-term mechanical reliability of LNCBs. After three years of operation without material degradation, this reliability test was successfully concluded.

In Title IV (Acid Deposition) of the Clean Air Act Amendments (CAAA) of 1990, the NO_x emissions limit for cell burner boilers is 0.68 lb/10⁶ Btu, effective January 1, 2000. Cell burner boilers represent a significant share of U.S. electric generating capacity, with baseline NO_x emission levels between 1.0 and 1.8 lb/10⁶ Btu. The demonstration project goal of 50% NO_x reduction can provide a substantial reduction in total NO_x emissions, in some cases potentially meeting the Title IV limits. LNCB technology offers a reliable, inexpensive plug-in retrofit option that does not require pressure part and piping modifications.

B. Process Description

Cell Burner Boilers

Economic considerations, which dominated boiler design during the 1960's, led to the development of cell burners for achieving high system efficiency in compactly designed utility boilers. Cell burners are designed for rapid mixing of fuel and air to achieve high rates of combustion. The tight burner spacing and rapid fuel/air mixing minimize flame size while maximizing heat release rates and overall unit efficiency. However, this high-intensity combustion results in high temperatures which leads to high NO_x concentrations in the combustion gases.

A standard two-nozzle cell burner is illustrated in Figure 1. Each cell consists of two circular register burners mounted in close proximity to each other within one vertical assembly. These assemblies are located on opposite walls of the lower furnace. A mixture of coal and primary air

enters each burner and is dispersed radially outward into a secondary air stream by means of an impeller located at the furnace end of the nozzle. Secondary air from the windbox passes through an adjustable register into an annular passage around the coal nozzle. The register acts as both a flow control device and a swirl generator.

The use of conventional LNB systems in boilers equipped with cell burners requires major boiler pressure part modifications. This is because the cell burner throat openings are too small to permit the low burner air velocities required for delayed combustion. Further, optimum NO_x reduction is achieved by conventional LNBs when the heat release rate per unit volume is minimized. This is not readily achievable in a typical cell burner configuration which has closely spaced burners.

Low- NO_x CellTM Burner Technology

As illustrated in Figure 2, LNCB technology for NO_x emission reduction involves two changes. The lower circular burner in each cell is replaced with a B&W S-type burner, and the upper burner is replaced with a NO_x port. The S-type burner throat is enlarged so that it has the same fuel input capacity as the two-burner nozzles it replaces. An impeller, mounted at the exit of the lower burner, radially disperses the fuel-rich coal/air mixture. The impeller angle affects the flame shape and length, which have a direct impact on NO_x formation and reduction.

Secondary air for burnout under fuel-lean conditions is supplied to the NO_x port. This port is equipped with a sliding disk to control air flow, a pitot tube to measure air flow rate, and louvers at the outlet to control mixing of the air with the fuel-rich flame. Adjustable spin vanes in the burner barrel control the swirl of the secondary air to aid in shaping the flame.

The LNCB design is based on the principle of staged combustion to reduce NO_x emissions. The S-burner operates under fuel-rich, reducing conditions, typically with 60-70% of the theoretical air required for complete combustion of the fuel. The balance of the air is supplied through the NO_x port in the modified cell. This delays mixing of coal and air, which results in a decrease in the formation of NO_x from the oxidation of both fuel-bound nitrogen (fuel NO_x) and nitrogen in the combustion air (thermal NO_x).

The net effect of applying this technology to cell burner boilers is a 50% reduction in NO_x formation. Since the LNCB was designed specifically to fit standard two-nozzle cell burner openings and spacings, no major modifications to boiler pressure parts are required. The 50% NO_x reduction and the ease of retrofit constitute the key attractions of the technology.

Background Studies

B&W had previously carried out laboratory and pilot-scale studies with EPRI support to characterize LNCB burners. The results of these studies showed that (1) LNCBs are stable over the design burner operating range and (2) 50% or greater NO_x reduction is achievable with

acceptable impacts on CO, UBC, and FEGT levels. In addition to these studies, one of the 24 standard cell burners in a twin unit of JMSS4 was replaced with an LNCB to evaluate the mechanical reliability of LNCB burners. No material degradation was found after three years of operation with the replacement burner.

Design Modifications

The LNCB retrofit was installed in JMSS4 in the Fall of 1991. After initial testing, it was found that two design changes were required, as discussed below.

Replacement of Burner Impellers

Since initial operation of the LNCB retrofit at JMSS4 gave only about 35% NO_x reduction, it was decided to replace the 24 burner impellers by impellers having a shallower angle. This modification was successful and resulted in achieving the project goal of 50% NO_x reduction.

Revised Burner Configuration

The other change involved modifying the burner configuration by inverting alternating LNCBs in the bottom rows. This was done in an effort to mitigate high concentrations of CO and hydrogen sulfide (H₂S) detected in the furnace hopper. High levels of these toxic gas species pose a health hazard because JMSS4 is a pressurized unit. There was also concern that the reducing atmosphere would promote accelerated tube wall corrosion in the lower furnace. The revised configuration, shown in Figure 3, had the desired effect of minimizing CO and H₂S concentrations.

The decision to modify the burner configuration was made on the basis of numerical models developed by B&W to simulate the combustion conditions that lead to a reducing environment in the lower furnace. After these models were validated as benchmarks, they were used to predict the optimum LNCB configuration. The demonstrated success of the numerical modeling approach for mitigating high levels of CO and H₂S provides B&W with a design tool for tailoring future LNCB firing configurations.

Corrosion Studies

H₂S is not normally formed in, or emitted from, coal-fired utility boilers. However, it is produced from sulfur-bearing fuels under the substoichiometric air supply conditions characteristic of staged firing. H₂S is subsequently converted to SO₂ by oxidation with the excess air introduced through the NO_x ports. The presence of H₂S can lead to corrosion of the boiler waterwall tube surfaces through sulfidation. The resulting tubewall wastage is typically more severe than that experienced under the oxidative conditions in conventional boilers.

In view of this potential problem, H₂S concentrations were measured on corrosion test panel installed as part of the LNCB retrofit. The test panel was installed on the west sidewall, and ultra-

sonic testing (UT) measurements were performed on several sandblasted areas on the lower furnace walls. The test panel consisted of four sections of commercial coatings separated by bare carbon steel tubing. Near each corner of the corrosion panel, temperatures and furnace gas compositions were measured. In addition, O₂, CO, and H₂S concentrations were analyzed by extracting samples with a 28-ft long water-cooled probe.

Probing and analysis of the furnace gas were complemented by laboratory-scale corrosion studies. Based on the laboratory results on different alloys and coatings, equations were developed for estimating the corrosion rate of coated and uncoated metal tubes exposed to reducing combustion gases produced by firing coal under substoichiometric conditions. In addition, UT measurements were made on the waterwall tubes at the conclusion of the test program.

The results of the UT measurements were inconclusive. However, corrosion rates were determined to be satisfactory using destructive testing of selected samples of tube materials taken from the test panel. These results indicated that localized fireside corrosion occurred over 15 months of exposure to LNCB firing conditions. It was found, however, that the corrosion rate was no greater than that experienced with the original cell burner arrangement. In both the laboratory-scale and full-scale corrosion studies, the alloys and coatings tested showed excellent corrosion resistance, suggesting that alloys or coated tubes could be used in future commercial application of LNCB.

C. Project Objectives/Results

The objective of this project was to demonstrate LNCB retrofit technology for reducing NO_x emissions from coal-fired cell burner utility boilers. The project was designed to confirm pilot-scale results on a commercial scale, as well as to resolve those technical issues that could not be adequately addressed in an engineering study or in pilot-scale tests.

The project was conducted in three major phases: baseline testing, optimization testing (two weeks), and long-term testing (eight months). The performance goals and results were as follows:

- 1. Evaluate the ability of LNCB retrofit technology to reduce NO_x emissions at least 50% on full-scale cell burner boilers.**

NO_x emissions reductions between 50% and 60% were achieved over a range of loads and excess air levels. During the long-term testing, the average NO_x reduction was between 53 and 55%.

- 2. Achieve the NO_x reduction goal with no degradation of boiler performance or life of the unit.**

The NO_x emission reduction target was achieved with no adverse impact on boiler efficiency and operability. Some localized corrosion was observed on bare tubes, but the corrosion rate was no

greater than that experienced with the original cell burners.

3. Demonstrate that LNCB is an economically viable retrofit technology.

The LNCB retrofit at JMSS4 was successfully optimized and demonstrated in a long-term test. The simple plug-in design of the LNCB system avoids costly pressure part and piping changes, thereby resulting in favorable economics. DP&L continued to operate the LNCB unit, and B&W retrofitted several other full-scale cell burner boilers with LNCB firing systems.

D. Environmental Performance

The demonstration program achieved the goal of 50% or higher NO_x emissions reduction, while showing no adverse impacts in terms of unacceptable increases in other gaseous or particulate emissions. B&W and Acurex Environmental Corporation, an independent testing organization made both emission measurements. Fly ash samples were collected at the inlet to the precipitator to determine particle size and loss on ignition (LOI), which is a measure of UBC. Solid waste streams were sampled from the boiler bottom and the ESP hopper ash discharge for measuring UBC content. No measurements were done on wastewater discharges either before or after the LNCB retrofit.

E. Post-Demonstration Achievements

The LNCB retrofit system is a commercially available B&W product. Over 5,500 MWe of cell burner boiler generating capacity has been retrofitted in the United States, in most cases achieving more than 50% NO_x reduction. There are a limited number of available opportunities since plug-in burner technologies have been developed which generally have replaced the LNCB technology.

The LNCB project received *R&D Magazine's* 1994 R&D 100 award as "one of 100 most technologically significant products of the year."

III Operating Capabilities Demonstrated

A. Size of Unit Demonstrated

The demonstration project was conducted at JMSS4, which is a 605-MWe cell burner boiler. The boiler was fired with a Midwestern bituminous coal having about 1% sulfur. Coal properties are given in Table 1. Since JMSS4 is typical in design and size of the U.S. cell burner population, the results are representative of commercial-scale operation and should be applicable to the rest of the cell burner population.

The testing at the J.M Stuart Station occurred in three periods. The baseline testing began in October 1990 and was completed in November 1990. This testing provided baseline performance and emission data. The second phase consisted of parametric and optimization testing. The parametric testing was conducted in May 1992 after the LNCB burners were installed at JMSS4 to determine the optimum burner settings for the final burner arrangement. The optimization testing was performed in June 1992, and recorded the performance and emission levels of the unit under operation of LNCD burners at optimum burner settings. The long-term testing was conducted between December 1991 and May 1993.

B. Performance Level Demonstrated

Overall Accomplishments

Reductions of 53-55% in NO_x emissions, from a baseline level of $1.18 \text{ lb}/10^6 \text{ Btu}$ to about $0.53 \text{ lb}/10^6 \text{ Btu}$, were achieved at full load in long-term operation of the LNCB firing system, with minimal impacts on boiler operation and other emissions.

The two most important potential problems associated with LNCB firing operation, high concentrations of CO and H_2S in the lower furnace and accelerated waterwall corrosion, were mitigated by inverting some of the LNCB burners in the lower burner rows on the opposed walls. In addition, test panel tubes coated with chromia-forming materials were found to be corrosion resistant in long-term testing.

NO_x Emissions Reduction

As indicated previously, reaching the emissions target required replacing all the retrofit burner impellers with impellers having a shallower angle than was used initially. The other design change, namely inversion of alternating LNCBs in the bottom burner row to mitigate high CO and H_2S levels, did not affect NO_x reduction performance.

The NO_x reduction results are summarized in Table 2. At full load of 605 MWe, uncontrolled NO_x emissions averaged $1.18 \text{ lb}/10^6 \text{ Btu}$ (929 ppm). (In this report, all concentration data are expressed in terms of ppm by volume, corrected to 3% O_2). Under optimized LNCB operating

conditions, the full load NO_x emissions decreased to an average of 0.53 lb/10⁶ Btu (417 ppm). This represents a reduction of 55%, which exceeds the desired 50% reduction set forth as a project goal. Table 2 also shows the average NO_x emissions results obtained at intermediate (460 MWe) and low (350 MWe) boiler loads. At intermediate load, the NO_x reduction averaged 55%, while at low load it was 47%. This represents an adequate turndown ratio for boiler operation.

There was good agreement between the B&W and Acurex NO_x measurements, except for the baseline NO_x emissions at low boiler load, where the Acurex measurements were significantly higher (0.92 lb/ 10⁶ Btu for Acurex vs. 0.70 lb/10⁶ Btu for B&W). Using the Acurex baseline figure would give a NO_x reduction of about 60%. For the sake of conservatism, B&W reports a 47% NO_x reduction at low load based on its own measurements.

The results of this demonstration project show that LNCB retrofits on cell burner boilers can provide 50 to 60% reduction in NO_x emissions. Applying LNCB technology to the majority of the existing cell burner boilers in the U.S. would achieve a significant reduction in total NO_x emissions.

CO Emissions

A significant discrepancy was found between the baseline CO emissions measured by B&W and by Acurex. In spite of recalibration of the two analytical systems, this difference persisted through the optimization and long-term LNCB test periods. Under optimized LNCB operating conditions, the average CO emissions were measured as 55 ppm by B&W and 28 ppm by Acurex. Although this discrepancy remains unexplained, these levels of CO emissions are well below those regarded as acceptable by the power generation industry, typically 100-200 ppm. The results are summarized in Table 3.

Nitrous Oxide Emissions

Nitrous oxide (N₂O) is not listed as an air pollutant, but it is a greenhouse gas and can contribute to the destruction of the atmosphere's ozone layer. To determine whether N₂O was formed as a result of the LNCB retrofit, the flue gases were sampled for N₂O. Only negligible amounts (~1 ppm) of N₂O were detected.

Particulate Emissions

Fly ash particulate emissions were measured to determine the impact of the LNCB retrofit on the efficiency of the electrostatic precipitator (ESP). There was virtually no change in the ESP collection efficiency (99.43% under optimized LNCB firing vs. 99.50% under baseline firing conditions). However, under LNCB conditions there was an increase in small particulates upstream of the ESP, as reflected by a 67% decrease in median fly ash particle mass.

In addition to measuring fly ash loading upstream and downstream of the ESP, in situ fly ash

resistivity at the inlet to the ESP was determined. Fly ash resistivity was controlled under both baseline and LNCB retrofit operation by means of flue gas conditioning with sulfur trioxide (SO_3).

C. Major Operating and Design Variables Studied

Effect of Burner Zone Stoichiometric Ratio

One of the most important variables in combustion is the ratio of air to fuel. The theoretical air/fuel ratio, defined as lb air/lb fuel for complete combustion, is calculated from the composition of the fuel. Actual combustion conditions are defined in terms of the stoichiometric ratio (SR), which is the actual air/fuel ratio divided by the theoretical air/fuel ratio.

With the LNCB retrofit, the reduced SR in the burner zone lowers the flame temperature and delays the complete mixing of fuel and air, thereby prolonging the combustion process. The balance of the air is introduced through the NO_x ports to complete the combustion. This deep air staging gives highly fuel-rich conditions at the burner, resulting in a reduction in NO_x emissions of about 50%. Previous B&W studies determined that the optimum SR for the primary burner is 0.6 to 0.7.

Effect of Boiler Load

As shown in Table 2, boiler load had a significant effect on NO_x reduction performance. More detailed data are given in the B&W Final Report. At full load, the lowest NO_x emission in long-term testing, $0.45 \text{ lb}/10^6 \text{ Btu}$ (354 ppm) was measured with one pulverizer mill out of service. The burners normally supplied by the pulverizer out of service were also taken out of service. However, cooling air continued to be supplied to these idle burners, so that some additional air staging occurred. Thus, for a number of configurations with mills out of service, additional NO_x reductions were achieved.

At lower loads, operating with one mill out of service led to the lowest average NO_x emissions, ranging from 0.32 to $0.39 \text{ lb}/10^6 \text{ Btu}$ (250 to 305 ppm).

As indicated previously, CO emissions levels at all boiler loads were sufficiently low that they did not constitute a boiler operating problem.

D. Boiler Impacts

The results of the project show that boiler performance was not significantly affected by the LNCB retrofit. Boiler performance criteria are discussed in the following paragraphs.

Effect on Boiler Capacity

Maximum unit load was not altered by the LNCB retrofit, nor was the turndown ratio. Because

of the once-through design of the JMSS4 boiler, superheater steam temperature is controlled by the firing rate, and reheat steam temperature is controlled by attemperation. Under LNCB retrofit conditions, these controls were used successfully to maintain operation at maximum continuous rating. At lower loads, steam temperature control was achieved by varying the excess air.

Effect on Boiler Efficiency

In general, boiler efficiency when operating with the LNCB retrofit showed very little change from that at baseline conditions. UBC loss was higher, but this was partially offset by a decrease in the dry gas loss due to a lower economizer outlet gas temperature and a corresponding decrease in air heater outlet gas temperature. (Dry gas loss represents heat not recovered in the air preheater.)

Average boiler efficiencies are summarized as follows:

	<u>Boiler Efficiency, %</u>	
	<u>Pre-Retrofit</u>	<u>Post-Retrofit</u>
Full load	89.6	89.6
Intermediate load	89.7	90.1
Low load	90.2	90.4

Effect on Furnace Exit Gas Temperature

In the optimization testing, while the FEGT initially decreased by as much as 100°F from baseline values it soon recovered to within about 10°F of baseline. Aside from the initial drop, it appears that LNCB retrofit has negligible impact on FEGT. Reasons for the time-dependent change are not clear, but B&W attributes it to the possibility of ash buildup on the furnace walls or changes in thermal emissivity.

Effect on Heat Transfer Performance

Surface cleanliness is a measure of the heat transfer performance of each component of the boiler unit. While changes in the values of the cleanliness factor were found for the secondary superheater (SSH) compared with baseline and optimized LNCB operations, the overall performance of the SSH was not affected by the retrofit. After the retrofit, only minor changes were found in the cleanliness of other convective pass heat transfer surfaces.

Effect on Unburned Carbon

The installation of any LNB tends to increase UBC. During optimization testing, UBC was measured on both boiler bottom ash and fly ash. On average, UBC increased 28% compared to

the baseline level of 1% carbon in ash. With one mill out of service, UBC increased by 52%, resulting in a loss of 0.69% in boiler efficiency. As mentioned above, this loss was partially offset by the decrease in dry gas loss, so that there was little net impact.

Effect on Waterwall Corrosion

As discussed previously, H₂S was present in detectable quantities in one test panel location, which corresponds to the area of accelerated corrosion found under baseline cell burner boiler operation. However, the corrosion rates were not significantly higher than those measured under baseline cell burner operating conditions, indicating that localized corrosion due to sulfidation was already a problem in JMSS4 when operating with the standard cell burners.

All of the coated tube materials of the test panel exhibited excellent corrosion resistance during the 15-month exposure to reducing environments. Use of chromic-forming coatings on the waterwall tubes seems to be advisable for preventing excessive corrosion in sustained LNCB operation. Further study is planned to determine specific locations and extent of tubewall corrosion.

Effect on Burner Pressure Drop

Installation of any modified combustion device typically increases pressure loss and thus raises the static head requirement of the forced draft fan. The pressure drop associated with LNCB retrofits ranges from 0.5 to 2.5 inches of water. Most current systems have sufficient capacity to handle this added pressure drop.

Other Effects

A beneficial result of the LNCB retrofit was a significant reduction in the buildup of agglomerated "popcorn" ash and associated erosion on horizontal convective pass tubes experienced with the original cell burner firing configuration. Maintenance for the air heaters, fly ash handling equipment, and bottom ash handling equipment decreased as a result of the improved properties of the ash produced under LNCB retrofit conditions.

E. Commercialization of the Technology

At JMSS4, B&W demonstrated that LNCB technology is applicable to the retrofit of coal-fired boilers equipped with two-nozzle cell burners. As mentioned previously, B&W has retrofitted LNCB technology on nearly 5,500 MWe of cell burner boiler capacity in the United States. Since a number of cell burner boilers have been sold outside the United States under B&W license, an international market may exist for this technology, though plug-in burner technologies are the current commercial choice.

Design Capabilities

The LNCB retrofit project demonstrated B&W's capabilities to apply its numerical modeling techniques to cell burner boiler NO_x control design. The concept of cell burner modification has been successfully validated for achieving the stated goal of more than 50% NO_x reduction.

The specific LNCB burner arrangement used in the demonstration project was based on B&W's FLOW and FURMO numerical models of furnace gas flow, combustion and heat transfer. These models were used to derive strategies for mitigation of high CO and H₂S concentrations in the lower furnace, discussed previously.

The numerical models have been or will be used by B&W on a site-specific basis for future LNCB system retrofits. Field validation of the predictive corrosion rate equations developed during the course of this project should help in the selection of appropriate tube and coating materials for additional LNCB retrofit applications.

Commercial LNCB Installations

In addition to the results of the successful demonstration project, B&W has built a large database on LNCB technology incorporating experience with other commercial retrofit applications. B&W summarized the status of the continued LNCB operation at JMSS4 and six follow-on commercial contracts using this technology [10]. At JMSS4, the unit routinely operates at NO_x emission levels less than 0.58 lb/10⁶ Btu. At the Allegheny Power System (APS) Hatfield's Ferry Unit 2 (a 555-MWe cell burner boiler), 50% NO_x reduction from 1.17 lb/10⁶ Btu to 0.58 lb/10⁶ Btu was achieved. Based on this performance, APS contracted with B&W to retrofit Units 1 and 3, which are identical to Unit 2.

The next LNCB retrofit was Detroit Edison (DE) Company's Monroe Unit 1, one of four identical 780-MWe cell burner boilers. Each of these units is equipped with a furnace division wall, which alters the heat absorption rate, and fires a blend of bituminous and subbituminous coals with an average sulfur content of 0.82 wt%. B&W guaranteed a post-retrofit NO_x level of 0.52 lb/10⁶ Btu, with CO levels not to exceed 150 ppm. B&W's numerical modeling predictions again were used for design of the LNCB retrofit configuration, which was different from that used at JMSS4 and Hatfield's Ferry. This further validates the capabilities of B&W's models for LNCB retrofit design.

The results of initial performance tests indicate that the guarantee can be met. Although the NO_x reduction of 44% from the baseline level of 0.93 lb/10⁶ Btu was not as large as in the demonstration project, the NO_x emission level achieved with this lower baseline NO_x unit was lower, 0.52 lb/10⁶ Btu vs. 0.58 lb/10⁶ Btu. Contracts have been awarded to B&W by DE for retrofitting Monroe Units 2, 3, and 4.

Future Work

Burner zone heat release rate, furnace design, and coal type influence baseline NO_x emissions and thus impact the NO_x emissions reduction achievable with LNCB. Further work in the following areas would provide additional understanding to permit broad deployment of this technology to other cell burner boilers.

Corrosion rate. Continued corrosion evaluations would be desirable. It would also be useful to develop a database on corrosion rates for units burning higher sulfur content coals. It should be noted that, while the corrosion rate equations developed in this program provide reasonable agreement with boiler test panel measurements over 15 months, they cannot predict corrosion rates over longer time periods due to fluctuations in oxidizing and reducing conditions and thermal stresses that prevail in commercial boilers.

Three-nozzle cell units. Potentially, LNCB technology could be adapted to three-nozzle cell burner configurations also, but there has been no experimental work to explore this concept. Because there are only a few three-nozzle cell burners in existence, an R&D program does not seem to be warranted. Instead, B&W's numerical modeling capabilities might be applicable to prediction of the design and performance of LNCB retrofits for such units.

Broadening of modeling capability. B&W's successful use of its flow, combustion and heat transfer models to establish the benchmark LNCB burner configurations for the demonstration project and for subsequent commercial contracts is an impressive accomplishment. Eventually, it would be desirable to incorporate detailed kinetics of NO_x formation and reduction chemistry into these numerical models for further improvement of their predictive capability.

Particulate removal. As indicated previously, there is an increase in fine particulate formation associated with operation of LNCBs. Future work could include study of the efficiency of ESPs or other dust collection devices for removal of fine particulates. It would be of interest to determine whether there is a significant increase in small particulates downstream of the ESP. This can be a concern, since fine particulates are carriers of adsorbed air toxic substances.

IV Market Analysis

A. Potential Markets

Plug-in burner technologies have replaced the Low-NO_x cell burners as the current commercial choice in the United States. NO_x control technology should be applicable to all two-nozzle cell burner boilers. The U.S. total capacity for coal-fired cell burner boilers is about 26,700 MWe, consisting of 38 operating units. These units range in size between 200 and 1300 MWe, with 22 units falling in the range of 480 to 800 MWe. Five of these units, having a total capacity of 1,500 MWe, employ three-nozzle cell burners. Since neither the benefits nor the risks of applying LNCB technology to three-nozzle burners are known, these units cannot be included in the potential market at this time.

LNCB retrofits in place account for eight units having a total capacity of about 5,500 MWe. Six units having a total capacity of 5,600 MWe are not candidates for LNCB, since they either have been or are slated to be retrofitted with other technologies. The net market for future application of NO_x control technology is 14,100 MWe, consisting of 19 units. These figures are summarized as follows:

	<u>Units</u>	<u>Capacity, MWe</u>
Total U.S. cell burners	38	26,700
Three-nozzle units	5	1,500
Other technology sales, retrofits, and options	<u>6</u>	<u>5,600</u>
Net available LNCB market	27	19,600
Existing LNCB sales, retrofits, and options	<u>8</u>	<u>5,500</u>
Future available LNCB market	19	14,100

As stated previously, NO_x emissions from existing cell burner units range from about 1.0 to 1.8 lb/10⁶ Btu. The reduction in NO_x emissions which would result from applying NO_x control technology retrofits to the net available U.S. cell burner population was estimated by assuming an average value for uncontrolled NO_x emissions of 1.2 lb/10⁶ Btu, 50% NO_x reduction, a power plant capacity factor of 65%, and a heat rate of 10,000 Btu/kWh. Based on the net available market of 19,600 MWe (including the existing commercial LNCB applications), the total nationwide reduction in NO_x emissions would be on the order of 330,000 tons/yr. This is equivalent to about 20% of the total NO_x emissions from U.S. coal-burning power plants.

B. Economic Assessment of Utility Boiler Applications

LNCB Costs

Based on a 1994 estimate for a nominal 600-MWe unit, which is representative of the average size of the U.S. cell burner boiler population, the estimated capital cost is \$9/kW. Uncontrolled NO_x emissions are assumed to be 1.20 lb/10⁶ Btu, with 50% reduction achieved through application of LNCB. Assuming a 15-year project life, the levelized cost on a current dollar basis is 0.37 mills/kWh. This is equivalent to \$125/ton of NO_x removed. On a constant dollar basis, the levelized cost is 0.28 mills/kWh, equivalent to \$97/ton. These economics are given in more detail in Table 4.

Site-specific factors that will impact LNCB retrofit costs include:

- Controls upgrades This includes engineering and materials for boilers where original equipment is still in use. Where controls have been upgraded to include control of air flow to the individual burners of the two-nozzle cell (such as at the JMSS4 site); control revision costs should be minimal.
- Corrosion protection In general, staged combustion low-NO_x systems are potentially subject to furnace corrosion, depending on the coal sulfur content. Tube protection using coatings is recommended for medium to high sulfur coals. Also, corrosion is related to tube wall temperatures, which tend to be higher in supercritical boilers. Many such cell burner boilers are already equipped with coatings for furnace wall corrosion protection. These units do not require further protection, while for others an evaluation of the effect of the coal being fired or potential furnace corrosion is needed.
- Field installation The costs are site specific. B&W's experience indicates that the installation cost is about 85-100% of the material price.
- Fans As discussed previously, installation of LNCBs will typically increase the static head requirement of the furnace draft fan. Since most current systems have excess fan capacity, the economic estimate given above does not include costs for upgrading the fans.
- Miscellaneous factors While not required in all LNCB installations, flame scanners and lighters are sometimes added.

Comparison with Alternative NO_x Control Technologies

Considering the excellent performance, low cost and ease of retrofit of LNCB technology, competing NO_x control technologies are likely to be more expensive unless the system is an alternative plug-in low-NO_x burner design. Such a retrofit system has been reported by DB Riley [13].

American Electric Power's (AEP) Muskingum River Unit 5, a 600-MWe supercritical cell burner boiler, was retrofitted with Riley's Controlled Combustion Venturi (CCV) LNBs. Initial results showed NO_x emission reductions greater than 50% without the need for other combustion modifications, burner respacing, mill system and coal piping changes, or pressure part modifications. However, performance has deteriorated over longer-term operation. Initially, NO_x emissions decreased to 0.6 lb/10⁶ Btu, a 52% reduction, but subsequent emissions averaged 0.69 lb/10⁶ Btu. After switching to a lower sulfur coal, NO_x emissions increased to 0.75 lb/10⁶ Btu, or a reduction of only 40%. No explanation has been offered for this degradation in performance.

Riley is continuing optimization of the retrofit, as well as the evaluation of advanced CCV burner designs for application to AEP's cell burner boilers. No cost data were presented in the paper, but it seems reasonable to assume that a successful CCV retrofit might be competitive with LNCB, because they both involve simple burner modifications and/or replacements.

Other combustion modifications such as conventional LNB retrofits require burner respacing, repiping, and pressure part changes. As discussed previously, this is more expensive and requires longer outages than LNCB retrofits.

Post-combustion technologies such as SCR and SNCR do not appear to be competitive with LNCBs for cell burner boiler NO_x control. SCR has the capability of a larger percentage NO_x reduction than LNCB, but is more expensive. Although SNCR has low capital costs, scale-up problems might prevent its use with larger boilers, which represent the majority of the cell burner population. Even in those cases where SNCR would be technically feasible, LNCB technology is expected to be more cost effective because of its significantly lower operating costs.

V Conclusions

A field demonstration of an LNCB retrofit on a representative 605-MWe cell burner utility boiler was performed successfully. Project goals were achieved, namely 50% NO_x reduction without significant adverse impact on boiler operation or other emissions. The demonstration project produced valuable data for future LNCB retrofit installations, validated B&W's design methodology, and identified areas for future improvements. Specific findings and accomplishments include the following:

- The boiler at the host site was successfully modified to provide staged air combustion, with one of the burners of each two-nozzle cell converted to the same firing capacity as the original design and the other one converted into a NO_x port to provide secondary air. This arrangement achieved the desired degree of NO_x reduction at full load, using an SR of 0.6 - 0.7.
- NO_x reduction also exceeded 50% at three-quarters load and was only slightly less than 50% NO_x at 60% load. This represents an acceptable turndown ratio.
- Application of NO_x control technology to the remaining U.S. cell burner boiler population, with an average NO_x removal of 50%, would result in a total nationwide reduction in NO_x emissions of about 330,000 tons per year, or about 20% of the total NO_x emissions from U.S. coal-fired utility boilers.
- High concentrations of CO and H₂S in the boiler hopper were mitigated by inverting some of the LNCBs in the lower burner rows in the opposed wall-fired demonstration unit. This strategy was developed by utilizing B&W's numerical models of flow, combustion and heat transfer, using in-furnace probing to establish benchmarks for the models.
- There was evidence of corrosion in the lower furnace, presumably due to the exposure of waterwall tubes to the reducing environment. Sulfidation is believed to be responsible for the corrosion of carbon or low-alloy steel tubes typically used in the lower furnace. However, the tube surface corrosion rate determined at specific furnace locations was no greater than that prior to the retrofit. The H₂S concentration near the waterwalls can be measured on-line using a monitoring technique successfully developed by B&W in this project.
- High alloy tube materials and chromia-forming coatings exhibited excellent corrosion resistance. For future commercial applications of LNCB technology, tube wall coatings should be considered.
- B&W developed equations related to boiler corrosion based on laboratory studies with various coatings and alloys. The corrosion rates predicted by the equations were in good

agreement with measured values obtained from a corrosion test panel installed in the furnace waterwall.

- Boiler efficiency was not significantly affected by the LNCB retrofit. The small decrease in efficiency attributable to increased UBC was partially offset by a reduction in dry gas stack losses.
- No effect was found on CO, N₂O, and particulate emissions. The ESP efficiency remained the same as under baseline conditions. There were no adverse environmental impacts on solid waste discharges.
- This project demonstrated the applicability of LNCB technology to retrofit NO_x control for two-nozzle cell burner boilers, which represent a large majority of the U.S. cell burner installations. The powerful numerical modeling techniques available for optimum design of LNCB retrofit configurations should prove valuable in ongoing and future commercial projects.

To sum up, an effective, simple, and low cost technology for cell burner boiler NO_x control has been demonstrated. Ownership of the LNCB retrofit emission control installation has been transferred to the host, DP&L, where operation of JMSS4 with the retrofit LNCB firing configuration continues.

Further information from operating the demonstration unit will be useful for other LNCB retrofits. The success of the LNCB technology is evidenced by B&W's meeting performance guarantees on nearly 5,500 MWe capacity of cell burner boilers in the United States.

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Abbreviations

AEP	American Electric Power
B&W	Babcock and Wilcox Company
CAAA	Clean Air Act Amendments
CCT	Clean Coal Technology
CCV	Controlled Combustion Venturi
DE	Detroit Edison
DOE	U.S. Department of Energy
DP&L	Dayton Power and Light
ESP	electrostatic precipitator
FEGT	furnace exit gas temperature
LOI	loss on ignition
LNCB	Low-NO _x Cell™ Boiler
JMSS4	J.M. Stuart Station, Unit 4
SR	stoichiometric ratio
SSH	secondary superheater
UBC	unburned carbon
UT	ultrasonic testing

Table 1. Coal Properties

Coal Source	Midwestern Bituminous
Proximate Analysis, wt% (as received)	
Fixed Carbon	47.61
Volatile Matter	33.14
Moisture	5.55
Ash	<u>13.70</u>
Total	100.00
Higher Heating Value, Btu/lb	
Wet	11,880
Dry	12,578
Higher Heating Value, MJ/kg	
Wet	27.6
Dry	29.3
Ultimate Analysis, wt%	
Carbon	70.43
Hydrogen	4.75
Sulfur	1.06
Oxygen	7.95
Nitrogen	1.30
Ash	<u>14.51</u>
Total	100.00

Table 2. NO_x Emissions Reductions Achieved by LNCB

Retrofit Optimization			
Boiler Load MWe	Average NO _x Emissions ^a lb/10 ⁶ Btu (ppm) ^b		Average Reduction in NO _x Emissions
	Baseline	Optimized LNCB	%
605	1.18 (929)	0.53 (417)	55
460	0.94 (740)	0.42 (331)	55
350	0.70 (551) ^c	0.37 (291)	47

a Average of B&W and Acurex measurements

b Corrected to 3% O₂, dry basis

c Average of B&W measurements only. Acurex measurements average 0.92 lb/10⁶ Btu (724 ppm). Using the Acurex baseline figure, the NO_x reduction at 350 MWe is 60%.

Table 3. Average of CO Emissions (Post-Retrofit Optimization)Data given as lb/10⁶ Btu (ppm, dry @ 3% O₂)

	<u>B&W Data</u>	<u>Acurex Data</u>
Full load - baseline	0.05 (26)	0.25 (120)
Full load - all mills in service	0.12 (55)	0.06 (28)
Full load - one mill out of service	0.08 (38)	0.04 (20)
Low load	0.06 (27)	0.01 (5)

Table 4

Summary of Performance and Cost Data
1994 Dollars

<u>Coal Properties</u>	<u>Units</u>	<u>Value</u>
Higher heating value (HHV)	Btu/lb	11,900

Power Plant Attributes With Controls

Plant capacity, net	MWe	600
Power produced, net	10 ⁹ kWh/yr	3.42
Capacity factor	%	65
Coal fed	10 ⁶ tons/yr	1.41

NO_x Emissions Control Data

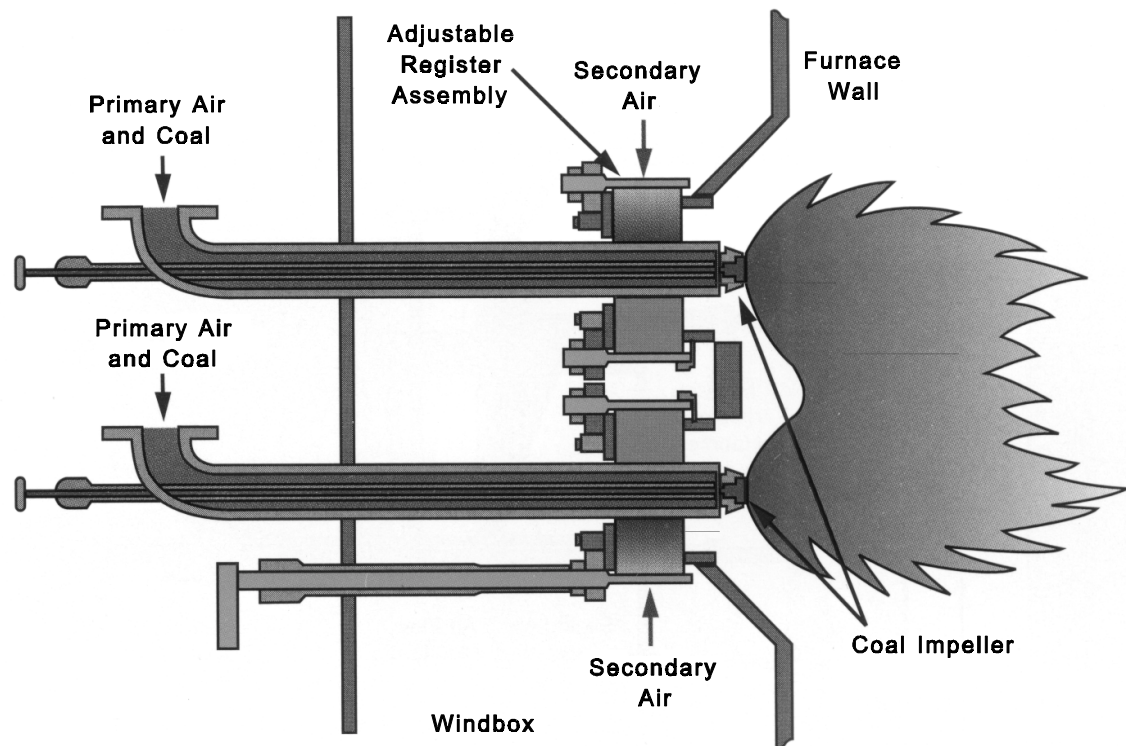
Removal efficiency	%	50
Emissions without controls	lb/10 ⁶ Btu	1.20
Emissions with controls	lb/10 ⁶ Btu	0.60
Amount removed	tons/yr	10,035

<u>Total Capital Requirement</u>	\$/kW	9
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	<u>Levelization Factor^a</u>	<u>mills/kWh</u>	<u>\$/ton NO_x removed</u>
<u>Levelized Cost, Current \$</u>			
Capital charge	0.160	0.254	86
Fixed O&M	1.314	0.017	6
Variable O&M	1.314	<u>0.098</u>	<u>33</u>
Total		0.369	126

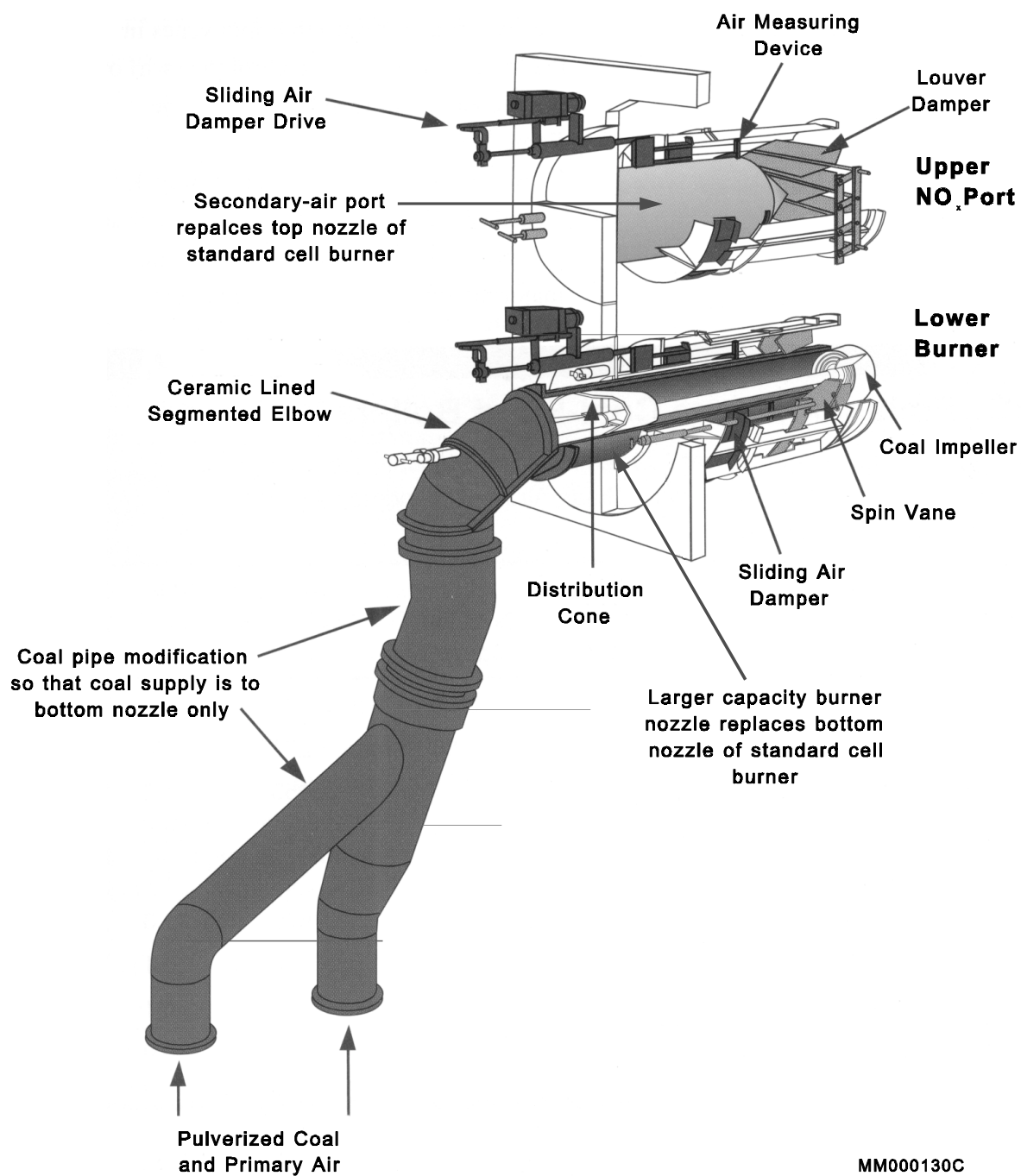
<u>Levelized Cost, Constant \$</u>			
Capital charge	0.124	0.196	67
Fixed O&M	1.000	0.013	4
Variable O&M	1.000	<u>0.074</u>	<u>25</u>
Total		0.284	97

a Levelization based on 15-year project life, 38% tax rate, 4% inflation, and the following capital structure: 50% debt @ 8.5% return, 15% preferred stock @ 7.0% return, and 35% common stock @ 7.5% return, giving a weighted cost of capital of 7.925% (including inflation).



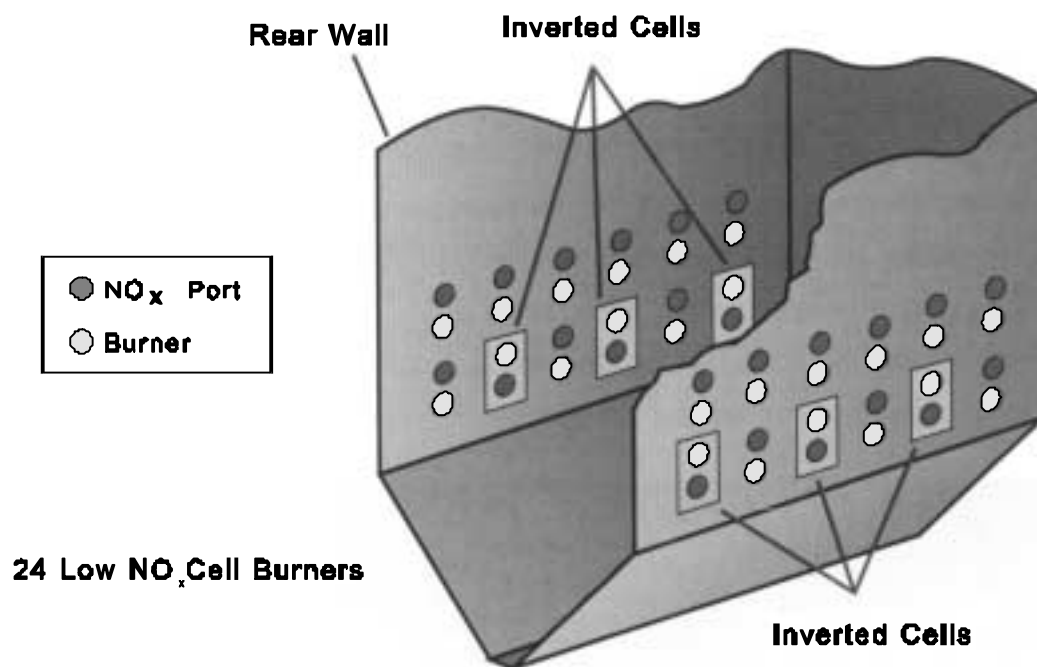
MM000131C

Figure 1. Two-Nozzle Standard Cell Burner



MM000130C

Figure 2. Low-NO_x Cell™ Burner



Dayton Power & Light Stuart #4 605 MW

Figure 3. Demonstration Site Furnace Configuration

NM000132C

